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# TESTS WITH STAGNATION-TEMPERATURE SENSORS HAVING AN INTERNAL CHANNEL BY THE EQUIVALENT PRESSURE DROP METHOD

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ABSTRACT

It is found that the proposed method for testing stagnation-temperature sensors has a high degree of accuracy and has several advantages over existing methods.

Air and gas streams are frequently measured by means of stagnation-temperature sensors having an internal channel whose narrow cross section (throat) contains a thermosensitive element (Ref. 4). Due to thermal exchange with a gas stream, the thermosensitive element acquires a temperature which is close to the stagnation-temperature recorded by the measuring device. /157*

The thermal exchange conditions, and consequently the thermometer readings, depend on the gas flow in the channel. Let us examine the features of this flow.

The velocities in different channel cross sections (Figure 1) are determined by the equation of mass flow

$$M_{\mathrm{sec}} = mF\frac{p^*}{\sqrt{T^*}}\,q(\lambda),$$

* Note: Numbers in the margin indicate pagination in the original foreign text.

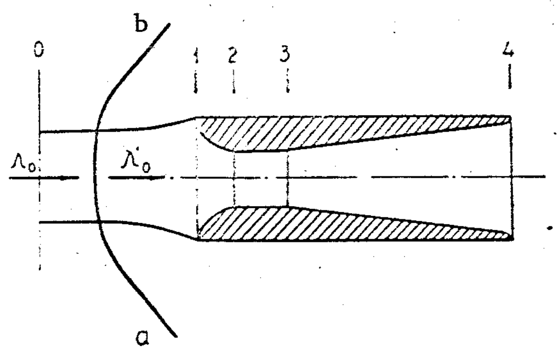


Figure 1

Gasdynamic Sensor Diagram

where

$$m = \sqrt{\left(\frac{2}{k+1}\right)^{\frac{k+1}{k-1}} \frac{k}{R}},$$

$$q(\lambda) = \left(\frac{k+1}{2}\right)^{\frac{1}{k-1}} \times \tag{1}$$

$$\times \left(1 - \frac{k-1}{k+1}\lambda^2\right)^{\frac{1}{k-1}} \lambda.$$

It can be quite accurately assumed that the gas flow in the channel does not receive or absorb energy; consequently, the stagnation temperature will remain constant along the entire stream T* = const. Then the condition of equal flow through the cross sections 0-0, 1-1, 2-2, 3-3, 4-4 can be written:

$$F_0 p_0^* q(\lambda_0) = F_1 p_1^* q(\lambda_1) = F_2 p_2^* q(\lambda_2) = F_3 p_3^* q(\lambda_3) = F_4 p_4^* q(\lambda_4) \tag{2}$$

(here F and p* are the areas of the channel transverse cross section and the stagnation pressures in the corresponding cross sections). /158

For small given velocities of the incoming stream $\lambda_0 = \frac{w_0}{a_{cr}}$, the flow is subsonic throughout the entire channel. In this case, when the velocity of the incoming stream $w_0$ changes, the velocities in the channel change. Cross section 3 corresponds to limiting gas flow. When $\lambda_3 = 1$, a blocking regime sets in, and the velocities remain constant on the 1-3 section, independently of $\lambda_0$. This is related to the fact that, in the case of $\lambda_3$ = $1q(\lambda_3) = 1$ and

$$q(\lambda_1) = \frac{p_3^*}{p_1^*} \frac{F_3}{F_1} = \sigma_{1,3} \frac{F_3}{F_1}, \tag{3}$$

i.e., in the case of $\sigma_{1,3} = \frac{p_3^*}{p_1^*}$ = const, a definite value of $\lambda_1$ is obtained for a given area ratio $\frac{F_3}{F_1}$. Consequently, the flow is stabilized in the contracting and cylindrical part of the channel, and the velocity change of the incoming streams is only manifested in the flow region in front of the inlet. That portion of the stream which enters the channel has the form of an expanding flow. This form occurs not only for the blocking regime, but also in the case of $\lambda_3 < 1$, when stream stagnation occurs in front of the input opening. This is due to the fact that there must be a pressure drop at the inlet and outlet in order to overcome the hydraulic channel resistances.

A detached head wave is formed for a supersonic velocity of the incoming stream $\lambda_0 > 1$ in the 0-0 cross section; the central portion of this wave can be regarded as a direct compression discontinuity. The transition through the shock wave is accompanied by the decrease in the given velocity

$$\lambda_0' = \frac{1}{\lambda_0}$$

(i.e., the stream becomes a subsonic stream), and also by a decrease in the stagnation pressure:

$$\sigma_{0,0'} = \frac{p_0^{*\prime}}{p_0^*} = \frac{q(\lambda_0)}{q(\lambda_0')} = \frac{q(\lambda_0)}{q\left(\frac{1}{\lambda_0}\right)}. \tag{4}$$

Isoentropic stream stagnation occurs up to $\lambda = \lambda_1$ between the head wave and the channel inlet opening, just as in subsonic regimes. The stagnation pressure in this section remains constant, i.e., $p_1^* = p_0^{*\prime}$. Therefore, we have

$$\sigma_{0,1} = \frac{p_1^*}{p_0^*} = \frac{p_0^{*\prime}}{p_0^*} = \frac{q(\lambda_0)}{q\left(\frac{1}{\lambda_0}\right)}. \tag{5}$$

As $\lambda_0$ increases, the head wave approaches the input opening, but it cannot overlap the inlet opening for the usually assumed channel contractions $\frac{F_1}{F_3}$, and penetrates within (Ref. 1, 2).

Thus, for all given velocities of the incoming stream, beginning with $\lambda_0 = \lambda_{0cr}$, for which the channel is blocked, the given local velocities /159 remain constant over all cross sections of the contracting and cylindrical portion. As a result of this, the thermal exchange conditions between the thermosensitive element and the gas stream are stabilized, and the local temperature recovery coefficient remains constant

$$r_x = \frac{T_{c.x} - T_x}{T^* - T_x},$$

where $T_{c.x}$ is the local temperature of the thermosensitive element wall,

$T_x$ - local, actual temperature in the stream.

The sensor performance coefficient

$$N = \frac{T_T}{T^*}, \tag{6}$$

which characterizes the extent to which the measured temperature $T_T$ approaches the stagnation temperature $T^*$, must also remain constant in these regimes. From $\lambda_0 = 0$ to $\lambda_0 = \lambda_{0cr}$, it must decrease from 1 to a value corresponding to the stabilized regime. However, technological deviations from structural dimensions and certain other phenomena caused the actual characteristics of the sensor $N = f(M_0)$ to be distorted, as compared with the theoretical characteristics. Therefore, before a sensor is placed in operation, it must be tested in order to determine the actual characteristics.

Such a test consists of placing the sensor in an air stream with a previously known number $M_0$ or a given velocity $\lambda_0$, and a stagnation temperature $T_0^*$. By comparing the measured temperature $T_T$ with $T_0^*$, one can determine the performance coefficient N according to formula (6). The experiment is repeated for different $M_0$. The characteristics are formulated according to the results obtained: $N = f(M_0)$ or $N = f(\lambda_0)$.

Another, more economical method of calibration tests can be recommended, which is essentially as follows.

It can be readily determined that there is a definite dependence between a given velocity of the incoming stream $\lambda_0$ and the ratio of the static pressure at the outlet of the channel $p_4$ to the stagnation pressure at the inlet to the channel $p_1^*$. It has the following form in subsonic regimes

$$\frac{p_4}{p_1^*} = \frac{p_0}{p_0^*} = \pi(\lambda_0) = \left(1 - \frac{k-1}{k+1}\lambda_0^2\right)^{\frac{k}{k-1}}, \tag{7}$$

and in supersonic regimes,

$$\frac{p_4}{p_1^*} = \frac{p_0}{\sigma_{0,1} p_0^*} = \frac{1}{\sigma_{0,1}}\pi(\lambda_0) = \frac{1}{\sigma_{0,1}}\left(1 - \frac{k-1}{k+1}\lambda_0^2\right)^{\frac{k}{k-1}}, \tag{8}$$

where $\sigma_{0,1}$ is determined according to formula (5) as the pressure recovery coefficient in the head wave.

The flow regime in the sensor channel is established in accordance with the pressure ratio $\frac{p_4}{p_1^*}$, independently of the manner in which it is achieved. This property lies at the basis of the equivalent pressure drop method. /160 Instead of placing a sensor in the supersonic gas stream, it is possible to only blow through its channel, thus artificially creating a pressure drop at the inlet and outlet which is equivalent to the operational regime. In this case, the velocities in the channel and the conditions for thermal exchange between the thermosensitive element and the gas are the same as in the operational regime, but the effort expended in producing the stream will be much less than in the usual wind tunnel. The fact that there is no head wave when the operational conditions are imitated in this way has no significant influence, since the stagnation temperature of the gas remains constant during the transition through the compression discontinuity. The only thing which may give rise to some doubts is the turbulence of the stream beyond the shock wave, which can appear in the boundary layer in the channel. It occurs under operational conditions, and is not present during tests using the equivalent pressure drop method. The experimental data given below show that this phenomenon is apparently insignificant.

When an equivalent pressure drop is artificially created at the inlet and outlet of the sensor, attention must also be paid to the conditions of the inlet and of the thermal exchange between the outer surface and the surrounding medium. The conditions under which air enters the channel must be reproduced as accurately as possible under operational conditions - namely, the bifurcation stream points must be located at the leading edge of the inlet opening. For this purpose, it is necessary to pass a small portion of the air through a thin layer outside of the sensor. This makes it possible also to imitate the temperature conditions on the outer sensor surface, since the stagnation temperature in the outer stream equals the stagnation temperature of the inner flow, as occurs under operational conditions. Therefore, thermal streams through the body walls are reduced to a minimum, and their order of magnitude and direction are the same as in an operational regime.

This method of testing stagnation temperature sensors was verified experimentally. Experiments were performed in a special UTPN-76 device (Ref. 3), which represented a direct-action wind tunnel with air pumped from the atmosphere and with an open jet - an open jet formed within the Eifel chamber when air is pumped in. For subsonic flow for M from 0.1 to 1.0, a contracting nozzle is employed which is designed according to the Vitoshin nozzle. For supersonic flows, Laval nozzles are used, which are designed for the given M numbers.

Two series of tests for the same sensor were formulated under the research program: the normal method and the equivalent pressure drop method.

For flow by the normal method, the sensor was placed in a UTPN-76 chamber, so that it was completely within the nucleus of the flow, i.e., it was subjected to a stream having a velocity which was equally distributed over the cross section.

For flows by the second method, a special nozzle 3 (Figure 2) was used, which was also designed according to the Vitoshin nozzle, but with decreased feed cross section. The diameter of its outlet opening exceeded the outer diameter of the sensor housing by a factor of 1.06 (Figure 2). When the sensor is located as is indicated in Figure 2 with respect to the nozzle, there is a pressure drop at the inlet and outlet. The main air mass passes through the channel, and a small portion flows against the outside surface through a thin layer, i.e., all of the conditions formulated in the pro- /161
posed method are maintained.

When the tests were performed, the temperature which was measured in the inlet tube (2, Figure 2), by means of the platinum resistance thermometer 1 and the high-resistance potentiometer PPTV-1, was used as the actual stagnation temperature. The stagnation pressure in the incoming stream was assumed to equal the pressure of atmospheric air. (It must be noted that

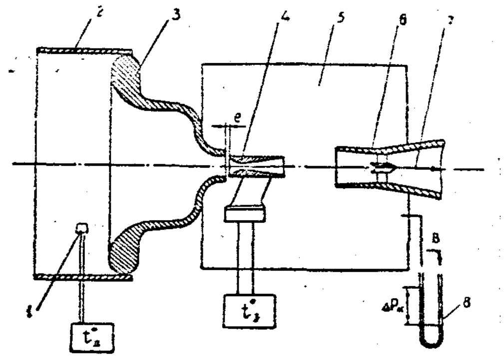

Figure 2

Diagram of Experimental Apparatus

1 - Platinum resistance thermometer; 2 - Input tube;
3 - Nozzle; 4 - Sensor employed; 5 - Operational chamber;
6 - Diffusor; 7 - Air direction; 8 - Mercury Piezometer.

temperature and pressure of the braked stream in the section encompassing the tube inlet up to the operational portion were held constant for the core of the flow in all preceding studies performed on the UTPN-76.) The static pressure at the outlet of the sensor being studied was assumed to equal the pressure in chamber 5, where it was measured by the mercury piezometer.

The resistance of the thermosensitive element was measured by the high-resistance potentiometer PPTV-1, and the temperature which the sensor measured was determined according to it.

The test results, a portion of which is presented in the graph in Figure 3, substantiate the reliability of the proposed method quite well. Curve 1 in Figure 3 represents the sensor characteristics N = f(M) obtained when it was tested by the usual method - flow in a wind tunnel. Curve 2 presents the characteristics of the same sensor recorded by the equivalent pressure drop method. As can be seen from the graph, the divergence in

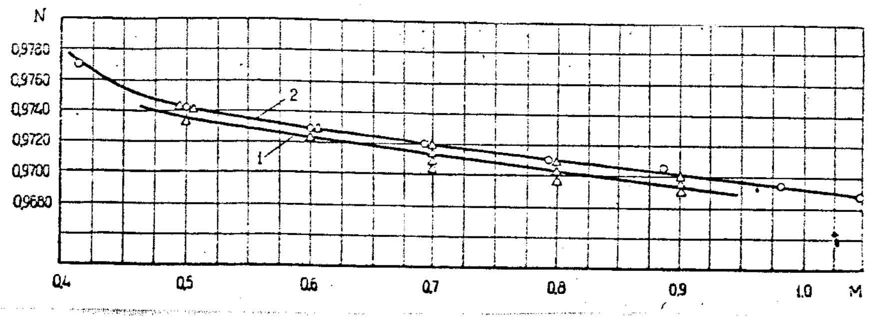


Figure 3

Dependence of the Quality Coefficient of the Temperature Sensor on the Number M of the Incoming Stream:

1 - Test in a wind tunnel; 2 - Test by the method of equivalent pressure drop.

the quality coefficient does not exceed 0.1%, and the nature of both curves is identical.

The influence of the nonalignment of the sensor 4 being studied with respect to the nozzle 3 (Figure 2) and the distance l between the planes of the nozzle outlet cross sections and the sensor inlet was also clarified during the test. The nominal dimension of the distance l was assumed to /162 equal the distance between the diameters of the nozzle opening and the sensor housing. It was found that small deviations of this distance from the recommended quantity, and also small nonalignment, do not produce significant changes in the quality coefficient.

The equivalent pressure drop method is very advantageous for conducting a series of tests as a standard. For this purpose, the test apparatus must have several nozzles which are in parallel. The sensor used as the standard must operate in conjunction with one of them - a test sensor or a control sensor, depending on the required accuracy. The characteristics of each sensor is controlled in this case by comparison with the characteristics of the standard sensor. Since both characteristics to be compared are obtained by one and the same method, any doubt that the test conditions do not correspond to operational conditions can be dispelled.

In conclusion, it must be noted that the proposed method of testing stagnation temperature sensors having a channel entails a very high degree of accuracy and has several advantages over existing methods - namely:

(1) It requires a small expenditure of power to produce the gas stream, since the main mass of the gas moves through a channel, and therefore it is highly economical;

(2) When the sensors are tested, supersonic streams are not employed; these streams usually entail prolonged work in designing and adjusting the Laval nozzles. Due to this fact, the construction of the test device and its operation are simplified considerably;

(3) The over-all dimensions of the test device are less than in a special wind tunnel, and considerably less than in an all-purpose tunnel;

(4) It is possible to perform tests not only in air, but also in other gases in a wide pressure and temperature range.

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